PCT

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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : G02B 5/30, 27/28, G02F 1/13

A1

(11) International Publication Number: WO 92/21046

(43) International Publication Date: 26 November 1992 (26.11.92)

(21) International Application Number: PCT/GB92/00844

(22) International Filing Date: 11 May 1992 (11.05.92)

(30) Priority data:
9110277.2 11 May 1991 (11.05.91) GB

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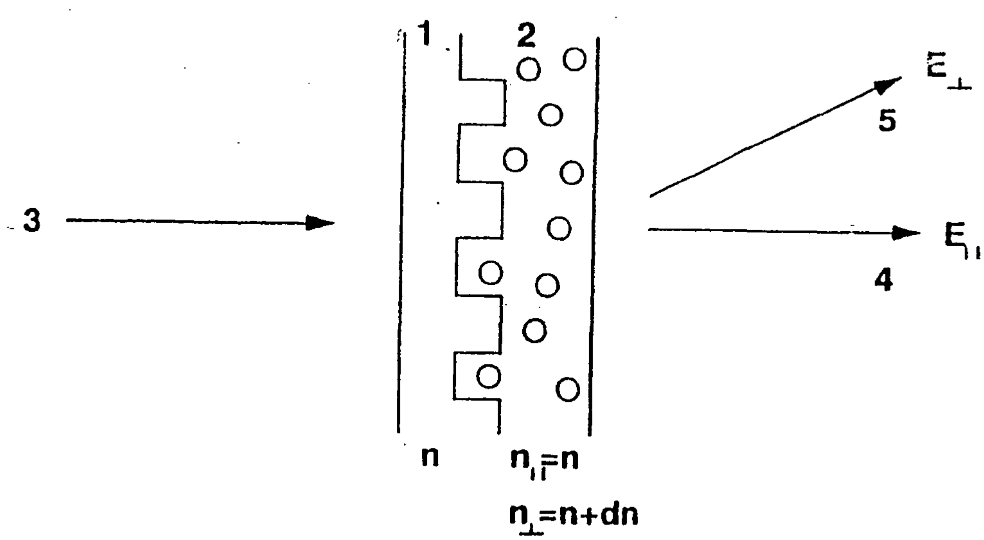
(81) Designated States: AT (European patent), AU, BE (European patent), CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB (European patent), GR (European patent), IT (European patent), JP, LU (European patent), MC (European patent), NL (European patent), SE (European patent), US.

Published
With international search report.

(54) Title: LIGHT SCATTERING DEVICE

Surface Relief Polarising Beamsplitter



(57) Abstract

A polarisation-selective or polarisation-productive optical scattering device is disclosed, which comprises an optically anisotropic material which is substantially transparent within at least a predetermined wavelength region, said material being disposed in a spatial pattern that comprises spaced zones, wherein at least one optical axis of said optically anisotropic material is at least locally substantially aligned with respect to said zones.

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LIGHT SCATTERING DEVICE

This invention relates to a light scattering device and, more particularly, is concerned with the production or selection of polarised light in optical systems.

Conventional polarisers, e.g. dichroic devices, when suitably oriented, allow one polarised component of incident light to pass, while the other component is absorbed internally. This presents a major problem for many high-energy applications, in that the absorbed component of the incident light heats up the dichroic material, and may cause the material to fail physically through structural disruption.

The ability of a periodic surface relief structure to generate diffraction patterns is well known. The book "Surface Relief Images for Colour Reproduction". Gale & Knop, Focal Press 1980, discloses that periodic surface relief grating structures may be used to produce wavelength selective diffraction. Gale and Knop have used this characteristic of surface relief structures to produce colour images using uncoloured slides. There is no disclosure in the book by Gale & Kemp which teaches the effects of a surface relief grating structure on the polarisation state of light.

A paper by Flanders et al published in Applied Physics Letters 32, 10, 15th May 1978, discloses that surface relief structures may cause alignment of the molecules of liquid crystal materials. There is no disclosure in this paper which teaches the effects of a surface relief grating structure on the polarisation of light.

We have devised a surface relief device (which we hereinafter refer to as a 'polariser')

which uses a spatially structured optically anisotropic material in order to selectively diffract polarised components of light passing through or reflecting from the device.

According to one aspect of the present invention, there is provided a polarisation-selective or polarisation-productive optical scattering device which comprises an optically anisotropic material which is substantially transparent within at least a predetermined wavelength region, said material being disposed in a spatial pattern that comprises spaced zones, wherein at least one optical axis of said optically anisotropic material is at least locally substantially aligned with respect to said zones.

The spatial pattern may be in the form of a linear grating, or in a form with circular symmetry.

Preferably the device is substantially non-absorbing within at least part of the wavelength region in which it is polarisation-selective so that it acts as a polariser without absorbing a significant amount of the incident light energy. This arrangement enables high brightness images to be produced in, for example, a projecting system, since a polariser constructed according to this invention can enable higher transmission or reflection of that polarisation selected to provide illumination, and/or lower absorption of at least the polarisation not selected to provide illumination in such a projection system.

The invention provides polarisers which are especially useful where the optical power absorption and heating which arise when a conventional polariser is used would limit the brightness of the output of the optical system. An example of such an optical system is a Liquid

Crystal Display (LCD) projector, in which liquid crystal is used in conjunction with polarisers to produce an image, although the invention may also be applied to laser or white light optical systems.

In one embodiment, the device comprises a substrate which is substantially transparent within at least a predetermined band of wavelengths and which carries the optically anisotropic material on its surface or within its bulk; this material is preferably arranged in a regular spatial array.

The optically anisotropic material may be a liquid crystal or liquid crystal polymer, or other optically anisotropic material. The optical axis of the optically anisotropic material is aligned relative to, and usually substantially parallel or perpendicular to, said linear pattern.

In an embodiment employing a substrate and to polarise normally incident illumination the material of the substrate and the optically anisotropic material are preferably chosen such that either the ordinary or the extraordinary ray in the optically anisotropic material experiences a refractive index generally equal to the refractive index of the substrate according to the formula $n(s) \approx n(1)$ where $n(s)$ is the index of the substrate and $n(1)$ is the index experienced by said ray, whilst the other ray experiences refractive index $n(2)$ given closely according to the formula $2d(n(s)-n(2)) \approx m\lambda$, where m is an odd integer, λ is the wavelength in vacuo of the light, d is a characteristic depth of said linear pattern. In the case that the linear pattern comprises rectangular troughs then d is the depth of the troughs. For linear patterns other than rectangular troughs then d is a value determined by the cross-sectional geometry of said linear pattern.

If these conditions are satisfied, normally-incident light of one polarisation is substantially diffracted into a plurality of diffraction orders, each characterised by a non-zero integer value k whilst normally-incident light of the other polarisation is transmitted undeviated. The device thus behaves as a beamsplitting polariser. If the materials of which it is made have low absorption at the wavelengths at which it is used the device has very low internal loss.

Similar relations to that given above hold for non-normal incidence and for the case of no substrate.

Light incident over a range of incident angles disposed around normal incidence is also substantially polarised or selected according to its existing polarisation state by this arrangement. Fabrication of the structure with materials for which the above conditions are not exactly met also produces a polariser enabling substantially polarised light to be produced or substantial selection of light according to its existing polarisation state.

In a first preferred embodiment of this invention said optically anisotropic material is supported by or incorporated within a substrate that is substantially transparent at least within a part of the wavelength region in which said disposition of optically anisotropic material is polarisation selective. Said substrate is preferably optically isotropic.

The substrate may take the form of a surface relief grating, e.g. of rectangular cross-section. It may take the form of a holographic diffraction grating. One currently preferred exemplar form of the invention comprises a surface relief structure formed within or on the surface of an optically isotropic substrate material

and an optically anisotropic material filling the troughs of that structure, one optical axis of the anisotropic material being aligned with the troughs. This form provides mechanical robustness.

In a second preferred embodiment the disposition of optically anisotropic material as a substantially linear spatial pattern is regular with well-defined period. This form produces well-defined diffraction orders each characterised by a value of an integer k.

In a third preferred embodiment the disposition of optically anisotropic material has a substantially linear spatial pattern which may be represented as the sum over a distribution of spatial frequencies from a non-zero lower limit of spatial frequency up to an arbitrarily high upper limit of spatial frequency. A typical convenient upper spatial frequency limit would be twice the reciprocal of the lowest optical wavelength at which the device is to be used.

Said second and third embodiments may be used in combination with said first embodiment.

In a fourth preferred embodiment forming a polariser with modifiable polarising or polarisation-selecting properties, the optically anisotropic material may be a material whose optically anisotropic properties, or the alignment of whose optically anisotropic properties with respect to the substantially linear disposition of the optically anisotropic material, may be controlled by external means. Some types of liquid crystals are suitable materials of this type since the alignment of their anisotropic properties may be continuously influenced by the application of an electric field. The application of this field may be local, within a limited

spatial region or regions of the polariser, or may extend across the entire optical aperture of the polariser.

A further example is a material which, in one phase or state has first optically anisotropic properties and in a second phase or state has optical properties which differ from said first properties. In this case means may be provided to switch or partially switch said optically anisotropic material from first said state or phase to second said state or phase. For example, other types of liquid crystal material are electrically switchable between said first and second phases or states. As a second example the material may be locally switched by locally-applied heat and the device thereby act as a thermally-written recording medium. This fourth embodiment may be used in combination with any of the previous embodiments described above.

In a fifth preferred embodiment of this invention the depth and cross-sectional geometry of the linear pattern is chosen to provide a colour-selective polariser. That is, a device providing an undeviated polarised output beam within a restricted wavelength range of ranges and/or a deviated polarised output beam or beams within a restricted wavelength range or ranges. In the case that the linear pattern has rectangular cross-section, then increasing the value of odd integer m described above reduces the width of the wavelength ranges in which the device provides undeviated polarised output beam. In the case of producing human - visible colours appropriate for display purposes from a white light source the values m=3 and m=5 are particularly advantageous. This fifth embodiment may be used in combination with any of the previous embodiments described above.

In a sixth preferred embodiment a colour-selective polariser as described above has mark to space ratio or cross-sectional geometrical form of the linear pattern chosen to provide the degree of colour saturation required for viewing. This sixth embodiment may be used in combination with any of the previous embodiments described above.

In a seventh embodiment of this invention the optically anisotropic material possesses within its bulk the property of rotating the plane of polarisation of light passing through it and has at both its entrance and its exit surface a linear surface relief profile of any of the forms described above. In a polariser according to this invention operating in transmission, such an arrangement may be formed for example by encapsulating a twisted nematic liquid crystal material layer between two substantially-parallel substrate layers each of which have a linear surface relief profile according to any of the forms described above. When the two linear surface relief profiles are mutually perpendicularly (or near-perpendicularly) angularly disposed light diffracted by one profile out of the incident-beam direction cannot be significantly diffracted back into the incident beam direction by the second profile. The liquid crystal (or other optically anisotropic material) may be arranged to have its local optical axis in its regions of its contact with each surface profile aligned with that profile (see, for example, Flanders et al, Applied Physics Letters, 32, 10, 15th May 1978) and in the bulk between those profiles to have its local optical axis rotate from alignment with one profile to alignment with the other. In this state illumination of the desired polarisation emergent undeviated from the first such profile will, by the polarisation-rotating property of the bulk liquid crystal (or other optically anisotropic material) be appropriately incident upon the second such profile again

to emerge undeviated from the second such profile. Further, traces of the undesired polarisation that should not have yet have, (perhaps through imperfect construction of first said profile) emerged undeviated from said first profile now be deviated by second such profile without redeviation of illumination already deviated by first such profile (and therefore of the undesired polarisation) back into the direction of the desired polarisation illumination. In this way further improvement in the separation of the desired and undesired polarisations may be obtained, and a higher quality polariser thereby obtained. This seventh embodiment may be used in combination with any of the previous embodiments described above.

For a better understanding of the invention, and to show how the same may be carried into effect, reference will now be made, by way of example only, to the accompanying drawings, in which:

Figure 1 is a scanning electromicrograph (SEM) of the surface relief structure of one embodiment of the invention;

Figure 2 is a diagram illustrating the structure shown in Figure 1, and explaining its mode of operation;

Figure 3 is a graph plotting the intensity of the undeviated beam (zero order diffracted beam) and the deviated beam as a function of wavelength with a device in accordance with the invention; and

Figure 4 is a schematic representation of two projection systems in accordance with this invention.

The device illustrated in Figure 1 consists of a grating structure 1 the troughs of which are filled with a optically anisotropic material 2 one of whose optical

axes is aligned with those troughs to form a polarising device (Figure 2). The optically anisotropic material is schematically represented as liquid crystal molecules aligned in the troughs of the grating structure. An input optical beam 3 is provided which is split by the device into an undeviated ray 4 and at least one diffracted ray represented by way of example by diffracted ray 5.

Figure 3 shows the spectral characteristics of the device intended for polarising blue light. The power of the deviated (5) and undeviated (7) polarised beams are shown plotted against wavelength. Compared to conventional dichroic devices, there is very little energy loss within the polariser. This means that the polariser of the invention is capable of use with higher energy levels than are conventional polarisers without undesirable heating of the polariser device.

In the projection system illustrated in Figure 4 the diffracted beams may be removed from the final output by using a stop 8 or other positionally - or angularly-selective optical means acting after polarising device 9. Alternatively a stop or other positionally - or angularly-selective optical means that prevents transmission of the undeviated beam (7) but which passes at least one of the deviated beams (6) may be used. One configuration is to place the device onto a substrate 10, and select the angle of the deflected beam 11 (for example, by adopting a grating with suitable spacing), such that at least some and preferably all of the deflected beams are totally internally reflected 12 in the substrate 1. In this latter case, a separate stop or other positionally - or angularly-selective optical means in the optical system is not required to obtain a high degree of polarisation or selection according to polarisation of the exiting illumination.

Where a liquid crystal is used as the optically anisotropic filling material, application of an appropriate electric field across the device will modify the optical axis orientation. The electric field may be localised within the optical aperture of the device or extend fully across that aperture. A device constructed in this way behaves as a locally - or fully-electrically-modifiable polariser.

The depth of the grating structure 1 may also be chosen such that the colour, (or wavelength) selection characteristics are more pronounced than those shown in Figure 3. In this way, a device in accordance with the invention may be constructed in such a way that it polarises blue light, for example, but allows green and red light to pass substantially unpolarised.

The device may also be used as a reflective polariser. In this case, and assuming normally - incident illumination and that grating 1 (Figure 2) has rectangular profile, the materials of grating 1 and the optically anisotropic material are preferably pairwise chosen so that either the ordinary or extraordinary ray in the optically anisotropic material experiences refractive index n(1) closely equal to the refractive index of the substrate according to the formula $n(s) = n(1)$ whilst the other ray experiences refractive index (n(2) closely according to the formula $d(n(s)-n(2))=m\lambda$ where d, n(s), n(f),m and λ are as defined above, and the structure including the optically anisotropic material may be placed on or incorporate a mirror such that incident light is reflected and passes twice through the structure. In this way, a reflective polarising device is constructed. Such a device need not employ a low absorption substrate material.

CLAIMS:

1. A polarisation-selective or polarisation-productive optical scattering device which comprises an optically anisotropic material which is substantially transparent within at least a predetermined wavelength region, said material being disposed in a spatial pattern that comprises spaced zones, wherein at least one optical axis of said optically anisotropic material is at least locally substantially aligned with respect to said zones.

2. A device as claimed in claim 1, wherein said zones are substantially linear.

3. A device as claimed in claim 1, wherein said zones possess circular symmetry.

4. A device as claimed in claims 1, 2 or 3, wherein said zones have a rectangular cross-sectional profile.

5. A device as claimed in claims 1, 2 or 3, wherein said zones have a sinusoidal cross-sectional profile.

6. A device as claimed in any preceding claim, wherein said pattern is regular.

7. A device as claimed in any preceding claim, wherein said pattern may be represented as a sum over a distribution of spatial frequencies from a non-zero lower limit of spatial frequency up to an arbitrarily higher upper limit of spatial frequency.

8. A device as claimed in any preceding claim, wherein said zones comprise a holographic element.

9. A device as claimed in any preceding claim, wherein said pattern is supported by or incorporated within a substrate material.

10. A device as claimed in claim 9, wherein said substrate carries said optically anisotropic material on its surface.

11. A device as claimed in claim 9 or 10, wherein said substrate is structured to provide a surface relief grating.

12. A device as claimed in claims 9, 10 or 11, wherein the ordinary or extraordinary ray within the optically anisotropic material experiences a refractive index closely equal to that of the substrate and the other ray experiences a different refractive index.

13. A device as claimed in claim 12, wherein said other ray locally experiences differential optical wavefront retardation of closely an odd integer number of half-wavelengths according to the spatial distribution of said optically anisotropic material pattern.

14. A device as claimed in any preceding claim, wherein a mirror or mirror layer is incorporated and polarisation selection is obtained in reflection.

15. A device as claimed in any preceding claim, wherein said optically anisotropic material has two faces both of which are capable to modify the wavefront of incident light, each of which incorporate a spatial pattern according to any preceding claim.

16. A device as claimed in claim 15, wherein said two faces form the boundaries of a liquid crystal cell.

17. A device as claimed in claim 16, wherein the two faces comprise linear grating structures of rectangular or sinusoidal cross-section orientated at 90^{o} to each other.

18. A device as claimed in any preceding claim, wherein said optically anisotropic material is a material whose optically anisotropic properties or the alignment of whose optically anisotropic properties with respect to the substantially linear zones may be modified by external means.

19. A device as claimed in claim 18, wherein said optically anisotropic material is switchable or partially switchable between said first and second phases or states.

20. A device as claimed in claims 18 or 19, wherein said optically anisotropic material is a liquid crystal.

21. A device as claimed in claims 18, 19 or 20, wherein said modification is local within part of the optical aperture of said device.

22. A device as claimed in claims, 18, 19, 20 or 21, wherein said modification is in accordance to an applied electric field.

23. A device as claimed in claims, 18, 19, 20 or 21, wherein said modification is in accordance to applied heat source.

24. A device as claimed in any preceding claim, wherein said polarisation selection or polarisation production extends over a limited wavelength range or ranges.

25. A device as claimed in claim 24 wherein said wavelength range or ranges lie within the human-visible wavelength range.

SEM of Surface Relief Structure

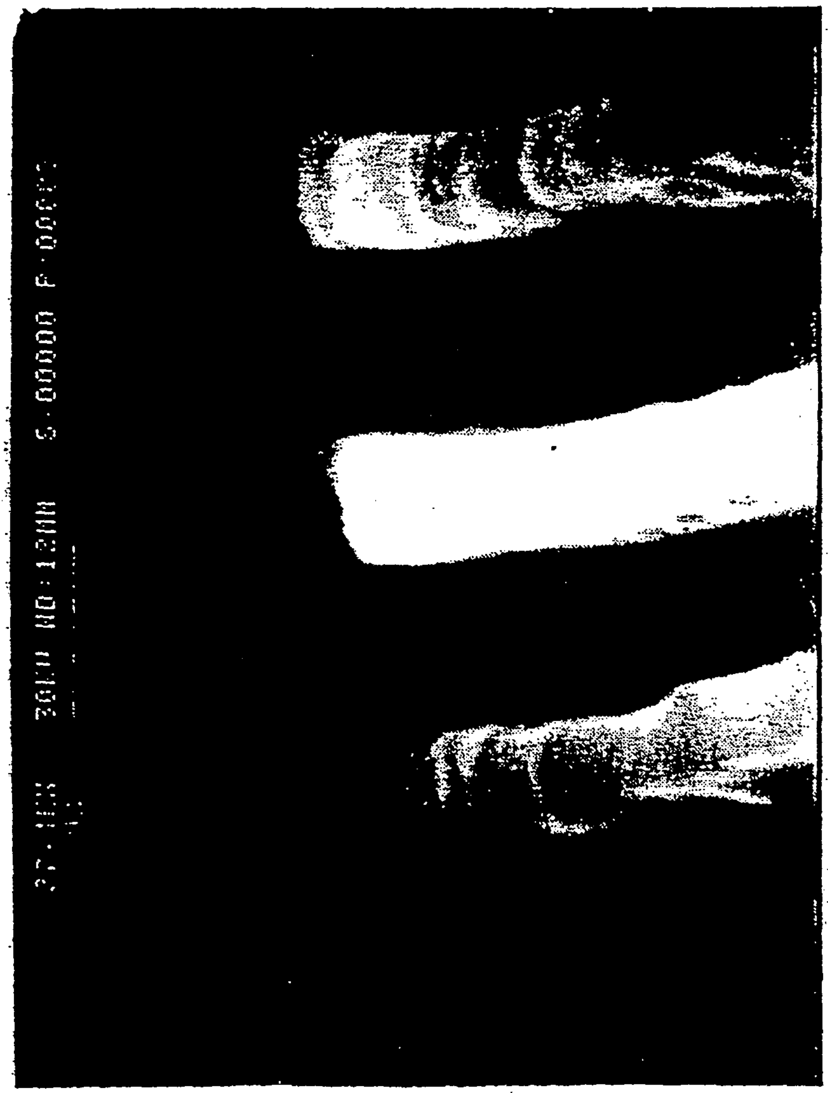

Figure 1

Surface Relief Polarising Beamsplitter

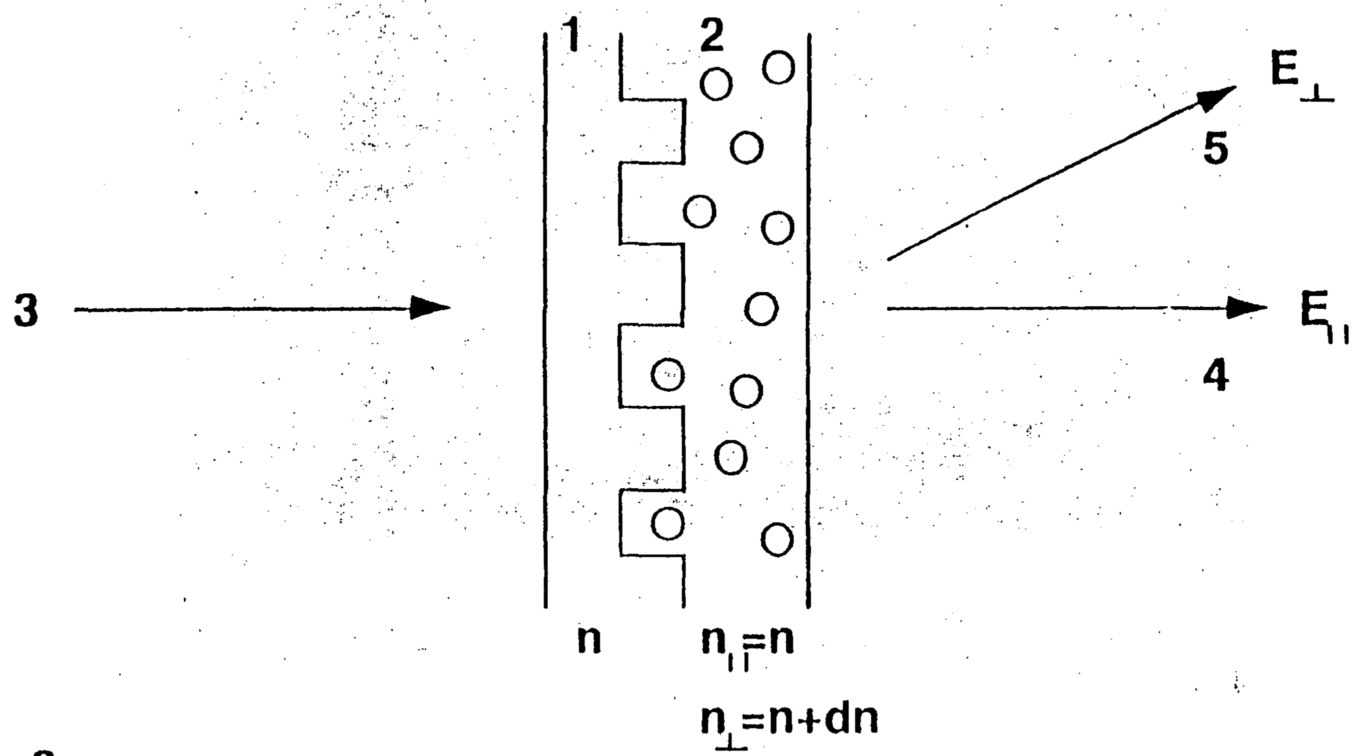

Figure 2

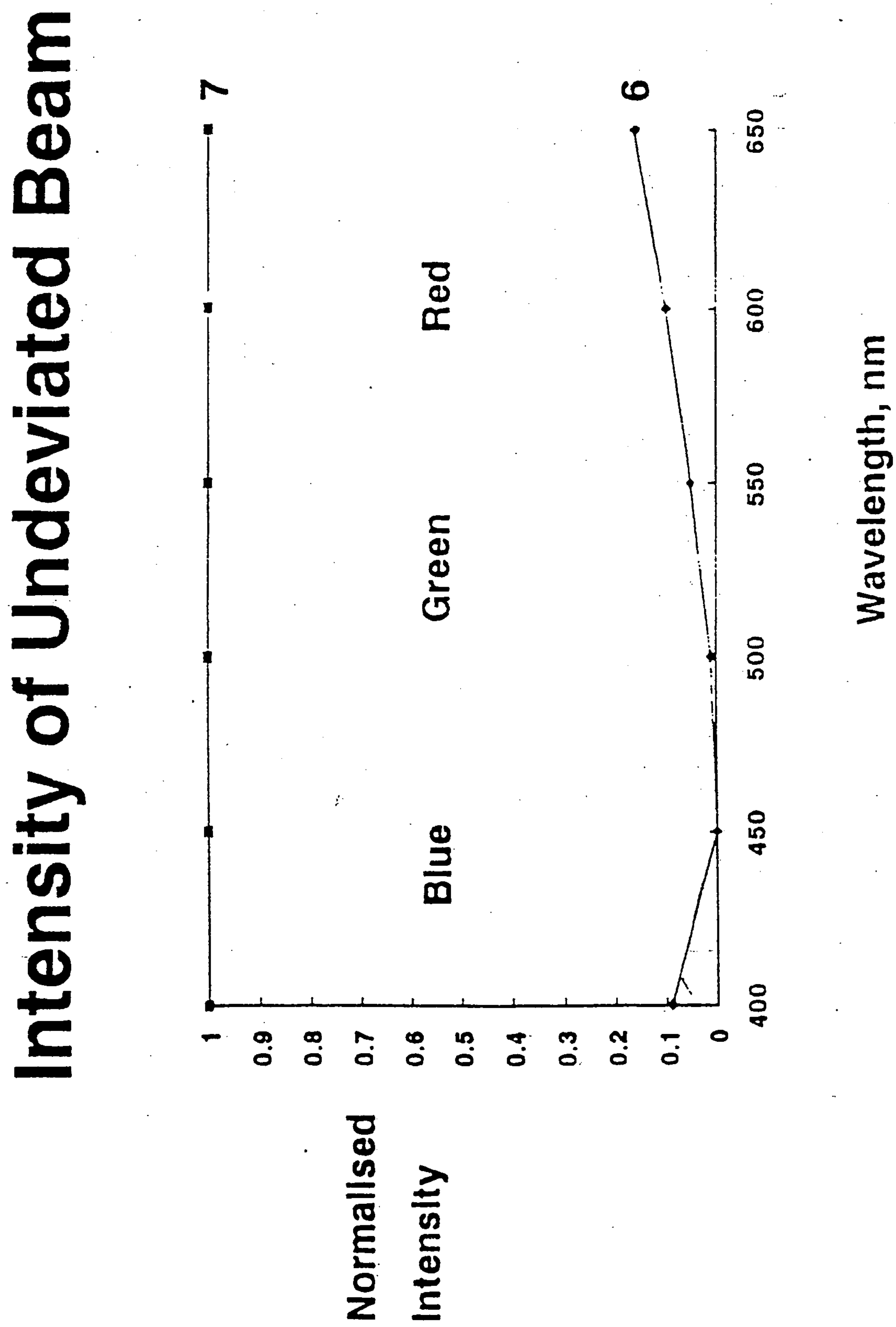
Intensity of Undeviated Beam
Normalised Intensity
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
400
450
500
550
600
650
Blue
Green
Red
7
6
Wavelength, nm

Figure 3

Polarising Projection System

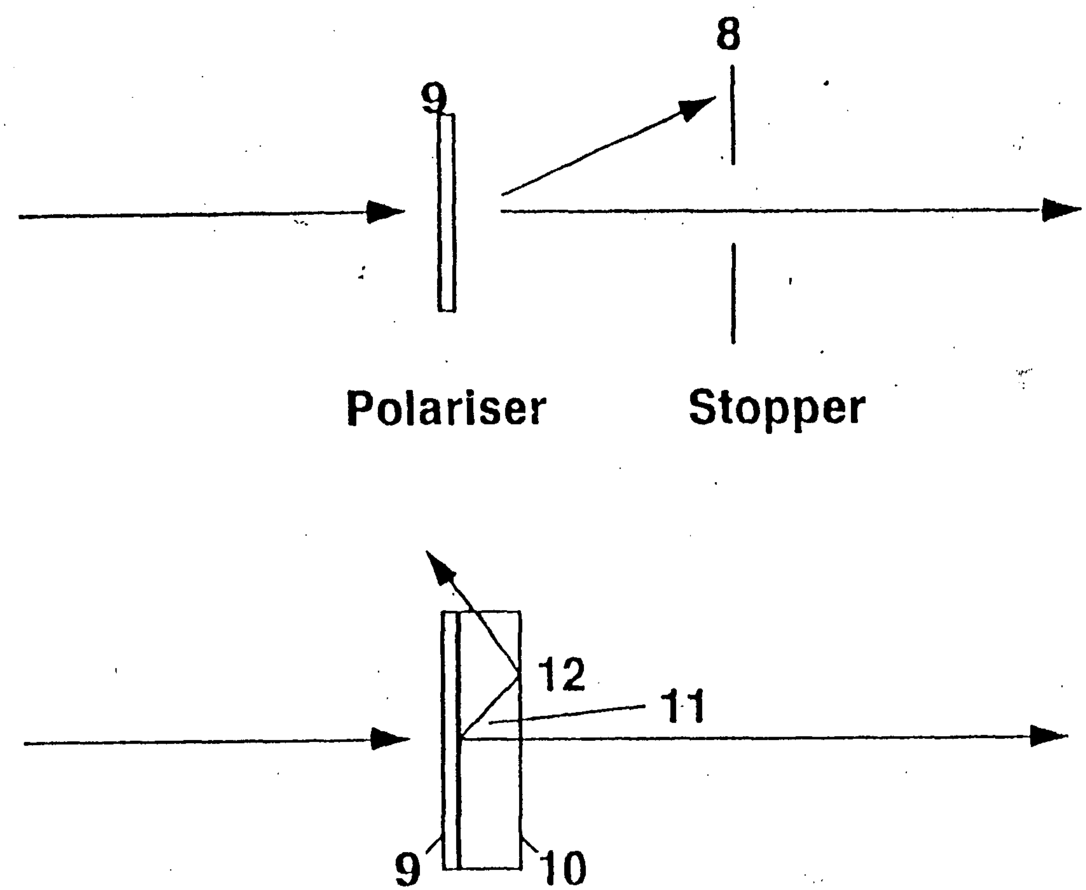

Figure 4

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 92/00844

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

IPC5: G 02 B 5/30, 27/28, G 02 F 1/13

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
IPC5	G 02 B; G 02 F

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category *	Citation of Document,[11] with indication, where appropriate, of the relevant passages[12]	Relevant to Claim No.[13]
X	GB, A, 2173605 (CANON KABUSHIKI KAISHA) 15 October 1986, see page 3, line 5 - page 5, line 55; page 9, line 32 - page 10, line 42; page 13, line 58 - page 14, line 7; abstract; figures 1-2,7-8,18	1-25
	--	
X	US, A, 4370194 (DAVID C. SHAVER ET AL) 25 January 1983, see column 5, line 15 - column 6, line 28; column 7, line 30 - line 49; figures 1-5	1-25
	--	
A	EP, A1, 0451034 (THOMSON-CSF) 9 October 1991, see column 3, line 42 - column 4, line 30	1
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"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
24th July 1992	19 AUG 1992
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	J. CARLERUD

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)		
Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
A	EP, A2, 0349144 (NEC CORPORATION) 3 January 1990, see the whole document --	1
A	US, A, 4856869 (HAJIME SAKATA ET AL) 15 August 1989, see column 11, line 10 - column 12, line 6 -- --------	1

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO.PCT/GB 92/00844

SA 59109

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report.
The members are as contained in the European Patent Office EDP file on 01/07/92
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Patent document cited in search report	Publication date	Patent family member(s)		Publication date
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		FR-A-	2577694	22/08/86
		JP-A-	61193105	27/08/86
		US-A-	5013141	07/05/91
		JP-A-	61193106	27/08/86
		JP-A-	61193122	27/08/86
		JP-A-	61193123	27/08/86
		JP-A-	61201214	05/09/86
		JP-A-	61203402	09/09/86
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		JP-A-	63218921	12/09/88
		JP-A-	62237425	17/10/87
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